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Transduction of the Spin State Variable Between the Electron and Optical Polarization at Zero Magnetic Field

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A New Spin on Electronics: Utilizing the spin degree of freedom of an electron in a semiconductor device is the basis for the emerging field of spin electronics, or spintronics.[1] The idea is that spin-polarized electrons can be introduced into a semiconductor host, and the electron's spin rather than charge can be used as a new state variable to produce performance and functionality not attainable by simply controlling charge motion (as is done in existing devices). To realize this new technology, it is first necessary to get spin-polarized carriers into the semiconductor, and NRL researchers are taking a lead role in this pursuit.

Our principal approach has been to electrically inject spin-polarized carriers from an Fe contact into an AlGaAs/GaAs light emitting diode (LED). In this system, we have been able to sustain electron spin polarizations of 40% to 70% in the GaAs. Further, we have uncovered a wealth of information on spin relaxation and transport phenomena through detailed spectroscopic studies. Most recently, we have been able to modify this system so that we can efficiently transduce spin angular momentum from the electrons to the photon optical polarization at zero magnetic field, a key step toward practical device applications such as spin-pumped laser diodes.[2]

Lighting the Way: The test devices commonly used to investigate spin injection are called spin-LEDs. In these devices, spin-polarized electrons are injected from a ferromagnetic (FM) metal like Fe, across a heteroepitaxial interface, through a semiconductor like AlGaAs, and into a GaAs quantum well (QW). In the QW, these spin-polarized electrons radiatively recombine with holes from the p-type substrate to produce circularly polarized light. Using quantum selection rules based on the conservation of angular momentum, we can directly relate the degree of light polarization, P_{circ}, with the spin polarization of the injected electrons, P_{spin}.

Out (of-Plane) with the Old: Typical spin-LEDs (Fig. 4(a)) use a narrow (~10 nm) QW recombination region in which quantum confinement constrains the hole angular momentum to lie along the surface normal (z-axis). For most thin FM films, out-of-plane is a hard magnetization direction. Consequently, a rather large external magnetic field (>0.5 T) must be applied to orient some component of the FM contact magnetization (and corresponding electron spin orientation) along the z-axis so that the electron and hole spins are colinear. It would be very advantageous to use the small coercive fields (<0.005 T) and large remanent magnetizations that FM metal contacts typically exhibit *in-plane.* This would greatly facilitate spin manipulation and transduction of the spin state variable between the electron spin and optical polarization for multifunctional device applications.

Observations at the Cutting Edge: By using light emitted from the *edge* of the spin-LED, we can fully benefit from the small in-plane coercive fields and large remanent magnetizations that our Fe contact naturally provides (Fig. 4(b)). Unfortunately, the story is not so straightforward as simply collecting light from the cross section of a device. By comparing light emitted from spin-LEDs in both the surface and edge emission geometry, we have discovered that details of the material system need to be fully understood to realize devices that can supply significant optical polarizations with small fields.

Figure 5 shows the circular polarization in the edge emission geometry as a function of applied field for several different QW widths. The inset is a photo of a spin-LED under test. For all fields, no circular polarization is observed from a system with a 10-nm-wide QW. This is expected because, as noted above, the hole angular momentum is constrained to lie along the surface normal and is thus orthogonal to the spin of the injected electron and light propagation direction. When wider QWs are used, the hole angular momentum can lie in-plane, colinear with the electron spin and light propagation direction. Hysteretic behavior of P_{circ} can be observed at very low fields (Fig. 6), demonstrating efficient electrical injection of spin-polarized electrons *even at zero field*.

A Wider Understanding: Even for wide QWs, the observed P_{circ} is much lower than expected at low applied fields, and the field dependence deviates significantly from the Fe magnetization data (Fig. 6), suggesting that some mechanism suppresses the optical polarization. We attribute the systematically lower polarization of the edge-emitted light to a partial out-of-plane orientation of the average hole angular momentum. In wide quantum wells, some fraction of the holes are weakly bound at the interfaces of the QW where the symmetry is reduced. This may arise from trapping at local interface potentials such as step edges, a well-known mechanism for the formation of quantum dots, or band bending in the semiconductor heterostructure. The angular momentum of such holes is then constrained to lie along the surface normal, as in the narrow 10-nm QW, and they do not contribute to the circular polarization of the edge-emitted light. This is an effect felt only by the holes, not by the electrons, and will not impact the performance of future spin-tronic devices based on manipulation of the electron spin system.

Summary and Implications: In summary, spin-polarized electron injection has been demonstrated in remanence using edge-emitting spin-LEDs with Fe contacts and wide quantum wells. These results demonstrate that spin-polarized injection is possible without an external magnetic field, and that the sign of the polarization achieved in the semiconductor is controllable with modest magnetic fields. These are key characteristics for spin manipulation and nonvolatile behavior in future device applications.

[Sponsored by NRL and ONR]

References

[1] For a recent review, see I. Zutic, J. Fabian, and S. Das Sarma, "Spintronics: Fundamentals and Applications," *Rev. Mod. Phys.* **76**, 323 (2004).

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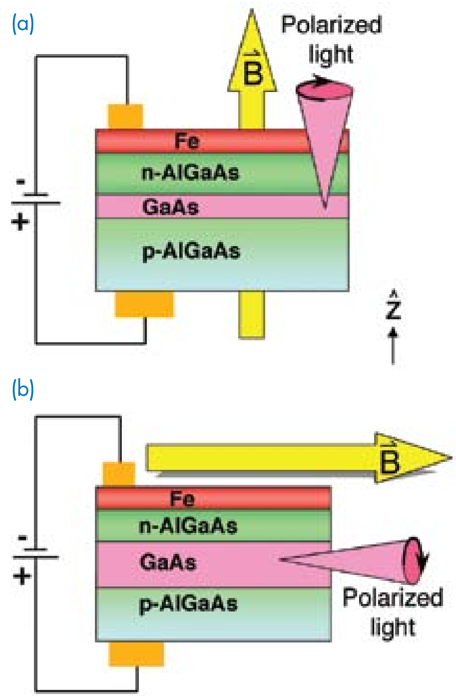

FIGURE 4
(a) Surface emitting spin-LED in the Faraday geometry, light from the active area travels through the Fe top contact. (b) Edge emitting spin-LED, light is emitted from a cleaved edge.

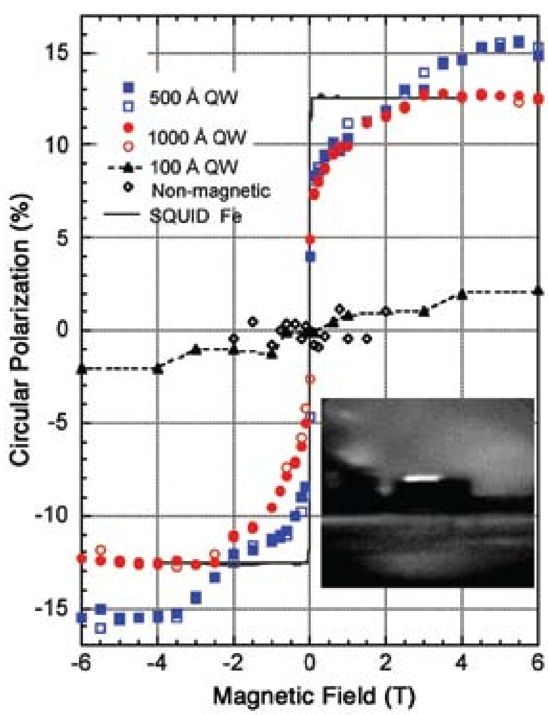

FIGURE 5
Electron spin polarization vs magnetic field at T = 20 K of edge emitting spin-LEDs with Fe spin injecting contacts and a 100-nm (circles), 50-nm (squares), and 10-nm (triangles) GaAs QW. The magnetic field is applied in-plane as shown in Fig. 4(b). The solid line is the in-plane magnetization measured by superconducting quantum interference device (SQUID) magnetometry at 20 K and scaled to the 100-nm QW data. The inset is a photo of a spin-LED under test.

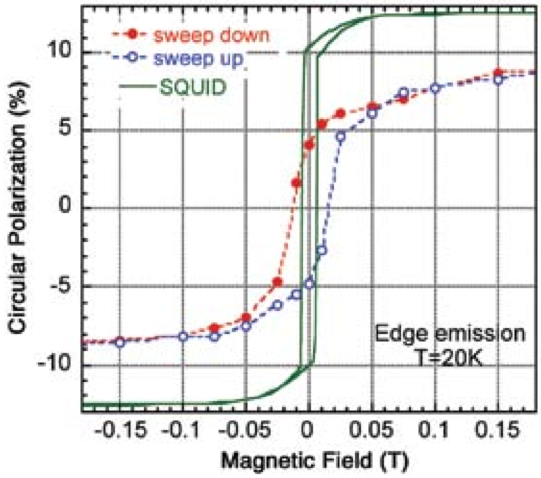

FIGURE 6
Optical polarization vs magnetic field of an edge-emitting spin-LED with an Fe contact and 50-nm QW at 20 K for small magnetic fields. The solid line shows the magnetization of the Fe film along the light propagation direction at 20 K.